

Middle Permian (Roadian) Foraminifera from mudstone facies of the type Baker Formation, Southern Carnarvon Basin, Western Australia

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Abstract

Foraminifera from the type section of the Baker Formation in the Merlinleigh Sub-basin are recorded for the first time. The sub-basin is part of a marginal rift that splayed from the main East Gondwana interior rift. It was inundated in the Cisuralian (Early Permian) and early Guadalupian (Middle Permian) by a shallow sea with estuarine-like water conditions. The formation forms part of a marine depositional sequence that extends from the uppermost Byro Group to the lower part of the overlying Kennedy Group. Its base is defined by a marine flooding surface and it forms the initial mudstone-dominated retrogradational to early progradational part of the sequence that is considered Roadian (early Guadalupian) in age (ca. 272–269 Ma). The Foraminifera are organic-cemented siliceous agglutinated types belonging to 21 species attributed to *Psammosphaera*, *Thuramminoides*, *Lagenammina*, *Placentammina*, *Psammosiphonella*, *Giraliarella*, *Hyperamminoides*, *Kechnotiske*, *Sansabaina*, *Ammodiscus*, *Hormosinoides*, *Reophax*, *Ammobaculites*, *Spiroplectammina*, *Palustrella* and *Trochamminopsis*. A new species, *Psammosphaera hockingi* n. sp. is described. Changes in assemblage composition through the succession suggest variable environmental conditions (including water depth and salinity) for the carbonaceous muds of this shallow interior sea, similar to those in some modern brackish interior seas and estuaries in temperate humid climatic belts.

KEYWORDS: Siliceous agglutinated Foraminifera; Permian; Merlinleigh Sub-basin; East Gondwana interior rift

INTRODUCTION

The Merlinleigh Sub-basin in the eastern Southern Carnarvon Basin (Fig. 1) contains a continuous Lower Permian to lower Middle Permian marine succession that has long provided a standard stratigraphic reference section for discussion of the Australian upper Paleozoic (Teichert 1941, Condon 1967, Hocking *et al.* 1987, Skwarko 1993, Mory & Backhouse 1997). Within this succession, the mudstone-dominated Baker Formation is the highest formation in the Byro Group, which is characterized by alternating mudstone- and sandstone-dominated units (Fig. 2). The type section of the Baker Formation designated by Condon (1954) lies on a west-facing scarp next to the headwaters of Blackheart Creek on Williambury Station at the northern end of Kennedy Range (Fig. 1b). Elsewhere in the Merlinleigh Sub-basin, the formation has been mapped in scattered exposures, mostly much poorer than the type section, widely separated by faults and large areas lacking outcrop, as well as in three bore sections remote from the type section (Condon 1967, Hocking *et al.* 1987). This has led to some correlations that may not be accurate, particularly when comparing isolated sections to the type section. Additional correlation methods are offered by biostratigraphy, sequence stratigraphy, including an appreciation of palaeobathymetric trends, and climatostratigraphy.

No fossils have been described from the type locality of the Baker Formation apart from a brief mention of the brachiopod “*Chonetes*” at two levels (Condon 1954, 1967). Previous biostratigraphic work on this formation has been undertaken on outcrop and boreholes remote from the type section (Skwarko 1993). Much of the previous work on the formation was done prior to the development of sequence stratigraphy as a method for interpreting outcrop successions (e.g. by Van Wagoner *et al.* 1990); and before an appreciation of East Gondwanan climate trends in different basin settings (see Haig *et al.* 2017). This lack of stratigraphic information has prompted our re-examination of the Baker Formation at its type locality. Our aim is to record the Foraminifera, the most abundant skeletal microfossil group found in the Western Australian Permian, from mudstone facies in this section and to interpret palaeobathymetric trends. This may provide a basis for better correlation of the formation elsewhere.

Geological Setting

During deposition of the Byro Group, the Merlinleigh Sub-basin was part of a shallow interior sea that formed along a narrow rift that splayed from a major rift system through the interior of East Gondwana along what is now the western margin of the Australian continent (East Gondwana interior rift; Haig *et al.* 2017). The interior sea was characterized by a very low gradient seafloor and highly variable water quality influenced by high input of freshwater laden with mud and fine sand. Periodically reduced freshwater inflow allowed the establishment

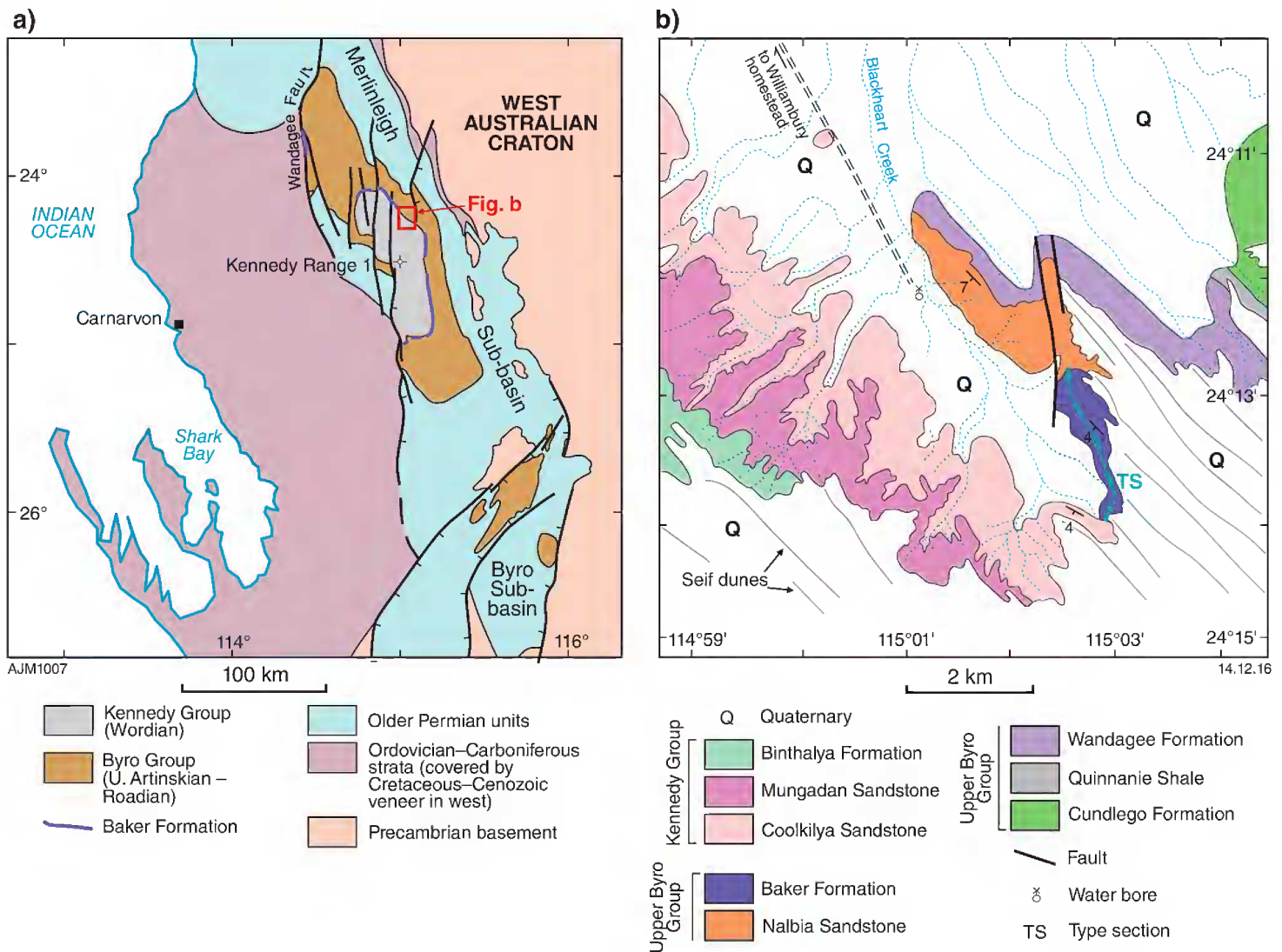
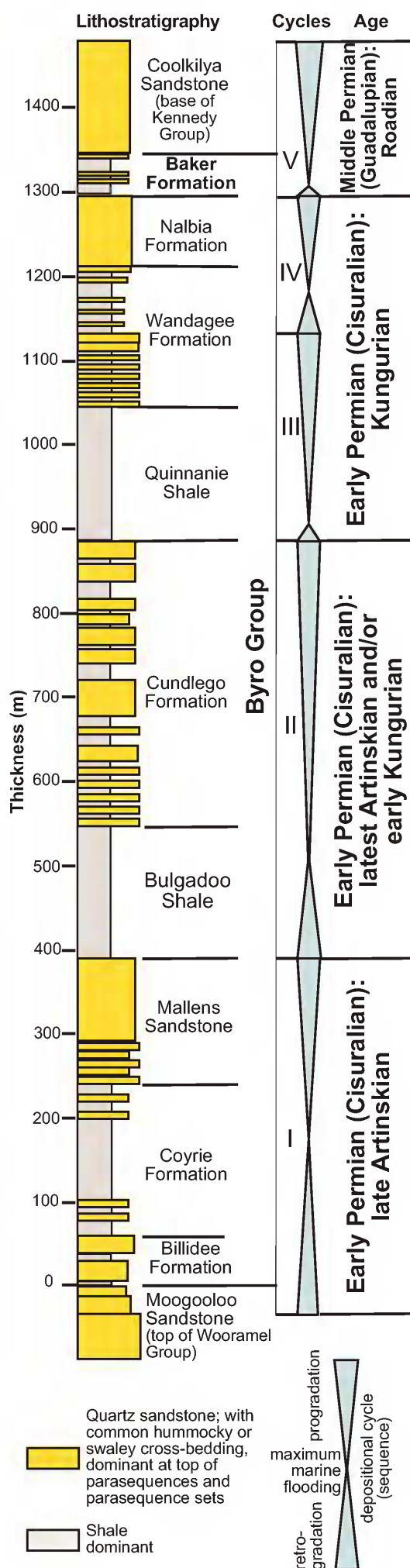


Figure 1. Geological Maps modified from Condon (1967): a) Southern Carnarvon Basin showing the positions of the Merlinleigh and Byro Sub-basins and the extent of the Byro Group within these; b) headwaters of Blackheart Creek showing the location of the type section of the Baker Formation.

Table 1. List of sample localities in type section of Baker Formation.

Sample	°S	°E	Location description
S1	24.22437	115.04791	1.7 m above base of formation; dark grey sandy mudstone with rare small bivalves
S2	24.22437	115.04791	3.4 m above base of formation; sandy mudstone with small scale bioturbation (sand-infilled burrows); jarositic layers
S3	24.22437	115.04791	5.1 m above base of formation; sandy blue-grey mudstone with small "pectens"
S4	24.22437	115.04791	10.5 m above base of formation, dark grey mudstone some sand laminae; about 0.3 m above 0.5 m thick mainly sandstone unit.
S5	24.22437	115.04791	12 m above base of formation; dark grey mudstone
S6	24.22437	115.04791	15 m above base of formation; dark grey mudstone
S7	24.22437	115.04791	16.8 m above base of formation; sandy mudstone
S8	24.22437	115.04791	18.7 m above base of formation; sandy mudstone
S9	24.22437	115.04791	20 m above base of formation; 20 cm above 40 cm-thick sandstone which is laminated at top and contains scattered Skolithos burrows
S10A,B	24.23028	115.04987	from mudstone unit about 2 m below contact with Coolkilya Sandstone



of normal-marine conditions and faunas, but restricted brackish water with estuarine-like conditions, similar to those in the present-day Baltic Sea, prevailed during deposition of most of the Byro Group (Haig 2003, 2004, Haig *et al.* 2014, 2017).

Material and methods

Along the scarp at the type locality (Figs. 1b, 3), no one vertical section transects the entire Baker Formation which dips at about 4° to the southwest. The Coolkilya Sandstone conformably overlies the southern part of the section whereas along most of the scarp the formation is overlain unconformably by flat-lying Cenozoic sandstone or is obscured by scree from this sandstone. For this study, the stratigraphic section was compiled by measuring the thickness of the basal mudstone unit using an abney level and then estimating the thicknesses of overlying units with the help of a series of photographs taken along the scarp.

Friable mudstone samples (Table 1) were collected after digging into the outcrop to obtain the freshest possible material. In the laboratory, samples were disaggregated by boiling in water with added detergent and then washed over 2 mm and 150 µm sieves. The residues collected from these sieves were examined under reflected light using a stereomicroscope and foraminifera picked onto microfossil-sorting slides using a damp very fine (000) sable-hair brush. Selected specimens were photographed under reflected light using an Olympus BX51 microscope. For each specimen a series of images was taken at slightly different focal lengths and the final image rendered using the depth-map method in the Helicon Focus 4.2.9 program. The microfossils and unprocessed portions of each rock sample are housed in the collections of the Edward de Courcy Clarke Earth Science Museum at the University of Western Australia.

TYPE SECTION STRATIGRAPHY

Lithostratigraphy

The base of the Baker Formation at the type section (Figs. 3b, 4) is at a friable sandy mudstone bed that overlies a more indurated quartz sandstone unit (72 m thick) that was designated by Condon (1954, 1967) as the type section of the “Norton Greywacke”, but has since been referred to Teichert’s (1950, 1957) Nalbia Sandstone (McWhae *et al.* 1958; Dickins 1963). The stratigraphic top of the Baker Formation (Figs. 3d, 4) is present at the southern end of the type-section scarp where it was defined as the highest mudstone overlain by thick quartz sandstone of the overlying “Coolkilya Greywacke” (Condon 1954, 1967; = Coolkilya Sandstone of Teichert 1950).

Although all stratigraphic logs compiled for the type section show three main stratigraphic divisions including a lower unit of mostly carbonaceous mudstone, a middle

Figure 2. Schematic stratigraphic log of the Byro Group (modified from Haig *et al.* 2017) showing the succession of formations, depositional cycles and ages.

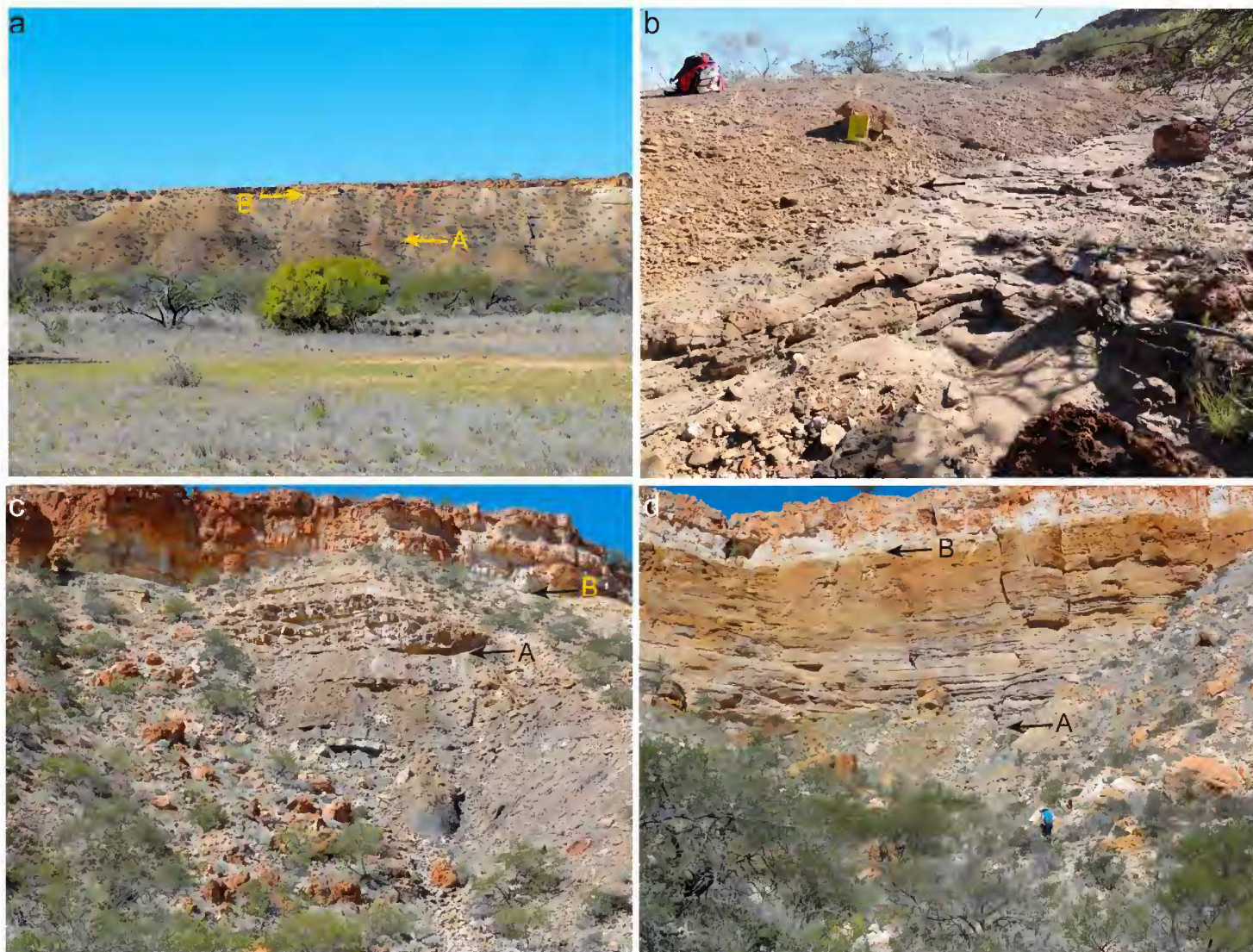


Figure 3. Outcrop photographs of parts of the type section of the Baker Formation: a) western-facing scarp (A, base of Baker Formation; B, unconformable contact with overlying Cenozoic sandstone); b) base of Baker Formation at marine flooding surface between underlying sandstone of the Nalbia Sandstone and overlying sandy mudstone of the Baker Formation; c) lower part of Baker Formation (A, boundary between lower mudstone unit containing several sandstone interbeds, and middle sandstone unit; B, unconformable contact with overlying Cenozoic Sandstone); d) north-facing scarp: (A, conformable contact between Baker Formation and overlying Coolkilya Sandstone; B, unconformable contact with overlying Cenozoic sandstone).

sandstone unit, and an upper unit of mainly mudstone, the stratigraphic thicknesses measured vary. Condon (1954, 1967) measured 60 m of strata forming the type section; Moore *et al.* (1980a) determined 52 m; we estimate a thickness of about 42 m (Fig. 4).

Friable sandy mudstone at the base of our measured section (Fig. 3b) contains calcareous spherical nodules, 2–4 cm in diameter, formed around pectinacean bivalves (now preserved as moulds). The lower mud-dominated unit (Fig. 3c) extends to 22 m above the base of the section and includes three sandstone beds with swaley and parallel laminations, each less than 50 cm thick, at about 9 m, 15 m and 19 m above the formation base. The mudstone adjacent the sandstone is sandy but elsewhere is dark-grey with a very minor sand component consisting mainly of quartz grains and siliceous agglutinated Foraminifera. No calcareous mudstone nodules were observed in the section, nor are there calcareous shell material or skeletal grains – extremely rare bivalve fossils are preserved as internal and external

moulds as the original very thin calcareous shells have been dissolved.

The middle unit, 22 m to about 37 m above the formation base, contains medium to thick quartz sandstone beds (Figs. 3c, 4). These were not sampled because well-sorted quartz sandstone usually lacks Foraminifera. Condon (1954, 1967) recorded a very thin “*Chonetes coquinite*” in mid-section of the unit. The upper unit includes a few metres of grey mudstone beneath the quartz sandstone succession of the Coolkilya Sandstone (Figs. 3d, 4).

Foraminiferal Biostratigraphy

Foraminifera are present in all the studied mudstone samples and are the only biogenic grains in the >150 µm washed sand component of each sample (Table 2). They are siliceous agglutinated species that originally constructed a test with siliciclastic grains (mainly quartz) held together by organic (glycoproteinaceous)

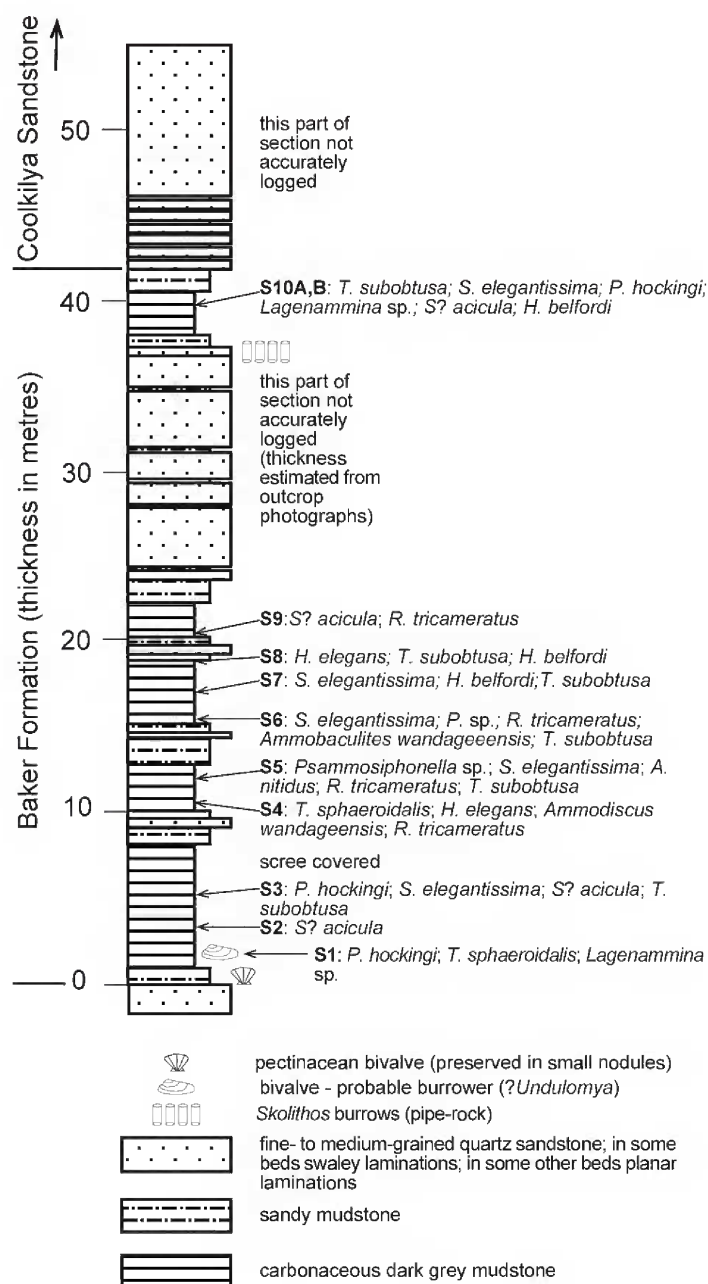


Figure 4. Stratigraphic log of type section of Baker Formation showing the positions of studied samples and the dominant foraminiferal species in each sample.

cement. During burial diagenesis, the flexible test deflates and deforms in various ways and the organic cement degrades. Over time, secondary quartz cement precipitates as interlocking quartz overgrowths on the silicate grains forming a rigid siliceous shell. Some of the tests originally had an organic inner lining and this seems still to be preserved in the initial whorls of some of the *Trochamminopsis* and *Palustrella*. These Foraminifera were very conservative in their evolution, with many genera ranging from the late Paleozoic through to the Cenozoic (Haig & McCartney 2010). No calcareous Foraminifera are present in the studied samples. It is possible that calcareous species were originally present in the life environment but their tests may have dissolved in the carbonaceous mud on the seafloor before substantial burial.

Within the Byro Group, siliceous agglutinated Foraminifera are the most abundant and persistent of any fossil group with mineralized skeletons (Parr 1942, Crespin 1958, Belford 1968, Palmieri 1993, Haig 2003, 2004, Haig *et al.* 2017). Frequent changes in foraminiferal assemblages noted by Haig (2003) and Haig *et al.* (2017) relate to high-frequency environmental changes with similar assemblages reappearing when comparable conditions returned to the depositional site. However, some broader biostratigraphic changes are also evident in the faunal distribution patterns that may be significant for stratigraphic correlation within the basin and between adjacent basins.

The foraminiferal fauna recovered from the type Baker Formation comprises 21 species (Table 2) and can be compared with assemblages listed by Haig *et al.* (2017) from formations of depositional cycles 1–3 of the Byro Group (Billidee Formation to lower Wandagee Formation) and the illustrated assemblages of Parr (1942), Crespin (1958), Belford (1968), Foster *et al.* (1985), Haig (2003), and Dixon & Haig (2004). Assemblages from depositional cycle 4 that includes the upper Wandagee Formation and Nalbia Sandstone (= Norton Greywacke), immediately below the Baker Formation, are very poorly known. All species from the Baker Formation but one are known from lower formations. The exception is *Hormosinoides* sp. cf. *H. expatiatius*, represented here by very few specimens. The recorded Western Australian distributions of the other species are listed in the RECORD OF FORAMINIFERA in this paper and are being revised in our continuing studies.

Comparison of successive assemblages in the type section (Table 2) suggests faunal composition changed frequently. Based on presence or absence of species, similarities range from 27% between samples S1 and S3 to 58% between S7 and S8. Dominant species also change from sample to sample (Fig. 4). Similar high-frequency changes are present in the older Quinannie Shale of depositional cycle 3, based on comparison of assemblages taken at 1 m intervals through a >190 m-thick mudstone succession (Haig 2003). The variability in faunal composition in the Baker Formation type section indicates that biostratigraphic comparisons for correlation purposes should be based on a series of samples, collected in the context of the sequence stratigraphy (see below) rather than a single sample.

Sequence stratigraphy

Based on broad patterns of retrogradation (i.e. marine transgression) and progradation (i.e. shallowing of marine conditions), Haig *et al.* (2017) recognized five major depositional cycles in the Byro Group (Fig. 2). The Baker Formation represents the initial retrogradational phase, maximum marine flooding interval and initial progradational phase of cycle 5, which incorporated the lower part of the overlying Cookiyla Sandstone as a late progradational stage. The base of the Baker Formation is a marine flooding surface initiated by an increase in water depths to below storm-wave base. The top of the Baker Formation at the transition from the uppermost mudstone to sandstone is indicative of shoaling to water depths consistently above fair-weather wave base. This boundary is conformable, as also recognized by Hocking *et al.* (1987), within a consistent progradational trend.

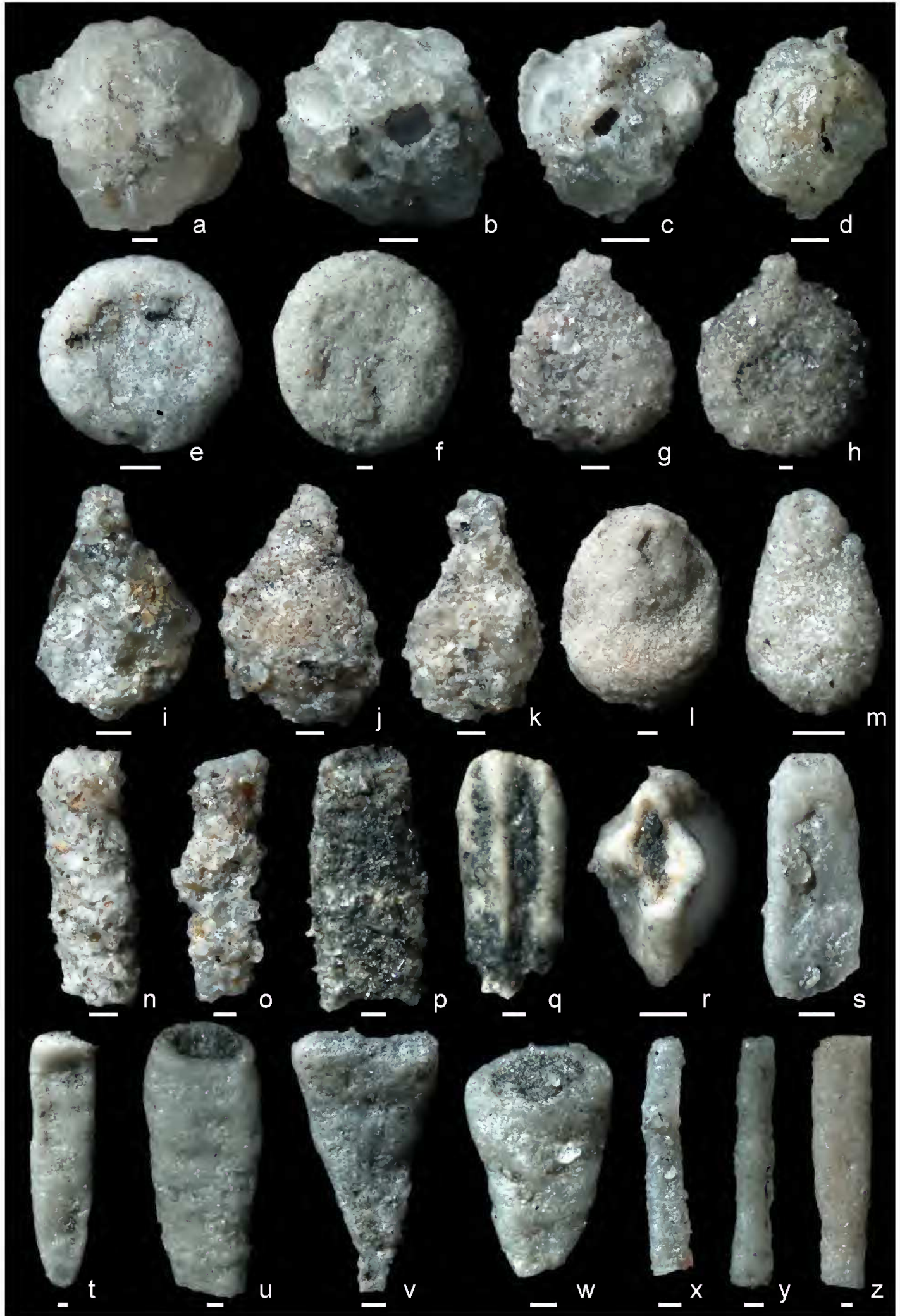


Figure 5. Foraminiferal images taken under reflected light and rendered from a series of photographs taken at slightly different focal lengths (bar scale = 0.1 mm). a–d *Psammosphaera hockingi* n. sp.: a, paratype, UWA172000, S3 from 5.1 m above base of Baker Formation; b, holotype, UWA172001, S10A from ~ 2m below top of Baker Formation; c, paratype, UWA172002, S5 from 12 m above base of Baker Formation; d, paratype, 172003, S10A from ~ 2m below top of Baker Formation. e, f *Thuramminoides sphaeroidalis* Plummer 1945: e, hypotype, UWA172004, S1 from 1.7 above base of Baker Formation; f, hypotype, UWA172005, S3 from 5.1 m above base of Baker Formation. g–k *Lagenammina* sp.; g, hypotype, UWA172006, S4 from 10.5 m above base of Baker Formation; h, hypotype, UWA172007, S1 from 1.7 above base of Baker Formation; i, hypotype, UWA172008, sample S4 from 10.5 m above base of Baker Formation; j, hypotype, UWA172009, sample S5 from 12 m above base of Baker Formation; k, hypotype, UWA172010, sample S5 from 12 m above base of Baker Formation. l, m *Placentammina ampulla* (Crespin 1958): l, hypotype, UWA172011, sample S5 from 12 m above base of Baker Formation; m, hypotype, UWA172012, S5 from 12 m above base of Baker Formation. n–p *Psammosiphonella* sp.: n, hypotype, UWA172013, S5 from 12 m above base of Baker Formation; o, hypotype, UWA172014, S5 from 12 m above base of Baker Formation; p, hypotype, UWA172015, S4 from 10.5 m above base of Baker Formation. q, r *Giraliarella rhomboidalis* Crespin 1958: q, hypotype, UWA172016, S3 from 5.1 m above base of Baker Formation; r, hypotype, UWA172017 sample S3 from 5.1 m above base of Baker Formation. s, t *Hyperamminoides elegans* (Cushman and Waters 1928): s, hypotype, UWA172018, sample S1 from 1.7 above base of Baker Formation; t, hypotype, 172019, sample S8 from 18.7 m above base of Baker Formation. u *Kechenotiske hadzeli* (Crespin 1958), hypotype, UWA172020, sample S4 from 10.5 m above base of Baker Formation. v, w *Kechenotiske expansa* (Plummer 1945): v, hypotype, UWA172021, sample S10A from ~ 2m below top of Baker Formation; w, hypotype, UWA172022, sample S6 from 15 m above base of Baker Formation. x, y *Sansabaina elegantissima* (Plummer 1945): x, hypotype, UWA172023, S4 from 10.5 m above base of Baker Formation; y, hypotype, UWA172024, sample S3 from 5.1 m above base of Baker Formation. z *Sansabaina? acicula* (Parr 1942), hypotype, UWA172025, S3 from 5.1 m above base of Baker Formation.

Table 2. Distribution of Foraminifera in studied samples from type section of Baker Formation

VR = single specimen; R = 2-5; C = 6-10; A = >10 specimens	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10 A	S10 B
Psammosphaeridae											
<i>Psammosphaera hockingi</i> n. sp.	C	VR	C	R	VR		R	R		A	R
<i>Thuramminoides sphaeroidalis</i> Plummer	C	VR	R	A		VR				R	
Saccamminidae											
<i>Lagenammina</i> sp.	C	VR		R	R	R			VR	R	C
<i>Placentammina ampulla</i> (Crespin)					R						
Bathysiphonidae											
<i>Psammosiphonella</i> sp.		VR		R	C	C	R	R	R		R
Hyperamminoididae											
<i>Giraliarella rhomboidalis</i> Crespin			R				VR			VR	
<i>Hyperamminoides elegans</i> (Cushman and Waters)	R		R	C	VR	R	?	A	R	?	?
<i>Kechenotiske expansa</i> (Plummer)						R			R	R	
<i>Kechenotiske hadzeli</i> (Crespin)	VR		VR	VR							
<i>Sansabaina elegantissima</i> (Plummer)	R		C		C	A	C	R	A	C	A
<i>Sansabaina? acicula</i> (Parr)	R	C	C			R	R		C	C	R
Ammodiscidae											
<i>Ammodiscus erugatus</i> Crespin	R		VR	R							VR
<i>Ammodiscus nitidus</i> Parr				R	C		VR			R	
<i>Ammodiscus wandageensis</i> Parr	R			C		?	R	VR	R	R	R
Hormosinidae											
<i>Hormosinoides belfordi</i> (Crespin)	R	VR	R		VR	R	C	C		C	R
<i>Hormosinoides</i> sp. cf. <i>H. expatiatu</i> s Plummer		VR									VR
<i>Reophax tricameratus</i> Parr	R	R		C	C	C		R	C		
Haplophragmoididae											
<i>Ammobaculites wandageensis</i> Crespin	R			R		C					
Spiroplectamminidae											
<i>Spiroplectammina carnarvonensis</i> (Crespin)						VR		VR	VR		
Verneuilinoididae											
<i>Palustrella improcera</i> (Crespin)	VR	R									
Trochamminidae											
<i>Trochamminopsis subobtusa</i> (Parr)			C		C	C	C	A		A	A
Similarity % with next highest sample (based on presence/absence)	38	27	29	44	47	41	58	50	38	44	

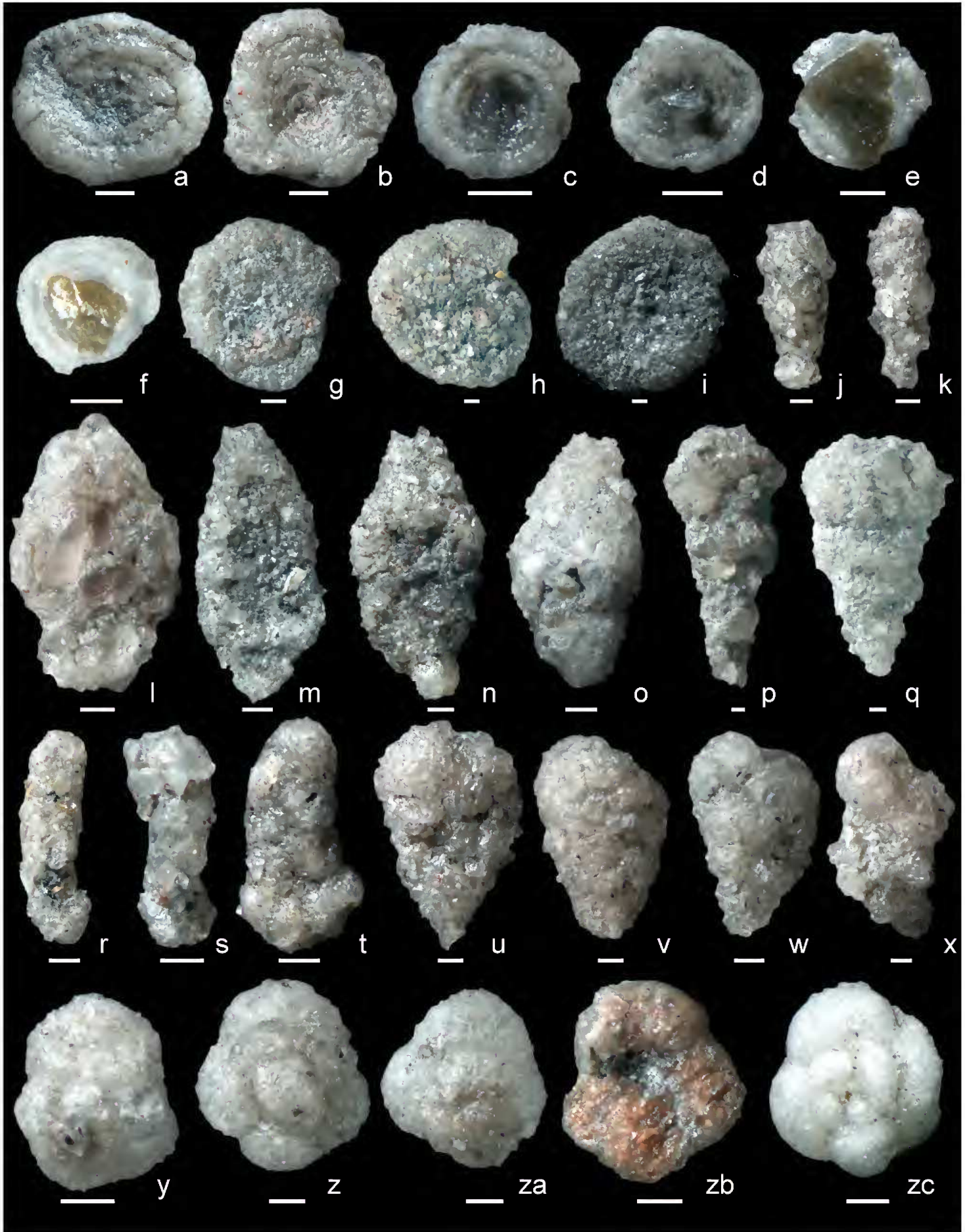


Figure 6. Foraminiferal images taken under reflected light and rendered from a series of photographs taken at slightly different focal lengths (bar scale = 0.1 mm). a, b *Ammodiscus erugatus* Crespin 1958; a, hypotype, UWA172026, S3 from 5.1 m above base of Baker Formation; b, hypotype, UWA172027, S1 from 1.7 above base of Baker Formation. c–f *Ammodiscus nitidus* Parr 1942; c, hypotype, UWA172028, S4 from 10.5 m above base of Baker Formation; d, hypotype, UWA172029, S4 from 10.5 m above base of Baker Formation; e, hypotype, UWA172030, S4 from 10.5 m above base of Baker Formation; f, hypotype, UWA172031, S10A from ~2m below top of Baker Formation. g–i *Ammodiscus wandageensis* Parr 1942; g, hypotype, UWA172032, S1 from 1.7 above base of Baker Formation; h, hypotype, UWA172033, S1 from 1.7 above base of Baker Formation; i, hypotype, UWA172034, S4, from 10.5 m above base of Baker Formation. j, k *Hormosinoides belfordi* (Crespin 1958); j, hypotype, UWA172035, S1 from 1.7 above base of Baker Formation; k, hypotype, UWA172036, S1 from 1.7 above base of Baker Formation. l–o *Reophax tricameratus* Parr 1942; l, hypotype, UWA172037, S1 from 1.7 above base of Baker Formation; m, hypotype, UWA172038, S4 from 10.5 m above base of Baker Formation; n, hypotype, UWA172039, S4 from 10.5 m above base of Baker Formation; o, hypotype, UWA172040, S5 from 12 m above base of Baker Formation. p, q *Hormosinoides* sp. cf. *H. expatius* (Plummer 1942); p, hypotype, UWA172041, S2 from 3.4 m above base of Baker Formation; q, hypotype, UWA172042, S10A from ~2m below top of Baker Formation. r, s *Ammobaculites wandageensis* Crespin 1958; r, hypotype, UWA172043, S1 from 1.7 above base of Baker Formation; s, hypotype, UWA172044, S4 from 10.5 m above base of Baker Formation. t *Spiroplectammina carnarvonensis* Crespin 1958, hypotype, UWA172045, S6 from 15 m above base of Baker Formation. u–x *Palustrella improcera* (Crespin 1958); u, hypotype, UWA172046, S1 from 1.7 above base of Baker Formation; v, hypotype, UWA172047, S2 from 3.4 m above base of Baker Formation; w, hypotype, UWA172048, S2 from 3.4 m above base of Baker Formation; x, hypotype, UWA172049, S2 from 3.4 m above base of Baker Formation. y–zc *Trochamminopsis subobtusa* (Parr 1942); y, hypotype, UWA172050, S5 from 12 m above base of Baker Formation; z, hypotype, UWA172051, S8 from 18.7 m above base of Baker Formation; za, hypotype, UWA172052, S8 from 18.7 m above base of Baker Formation; zb, hypotype, UWA172053, S3 from 5.1 m above base of Baker Formation; zc, hypotype, UWA172054, S5 from 12 m above base of Baker Formation.

Whereas Condon (1954, 1967) interpreted the boundary as disconformable and “in places unconformable”, Moore *et al.* (1980b) pointed out that the supposed erosion at this level (near the southern end of Kennedy Range) is along a faulted contact.

Higher frequency cycles are evident in the type section. Moore *et al.* (1980a) and Hocking *et al.* (1987) recognized two main mudstone–sandstone cycles and these are apparent in our measured section (Fig. 4). The presence of interbedded sandstone with swaley cross-bedding within the mudstone units and the frequent up-sequence changes in foraminiferal assemblages suggest higher frequency depositional cyclicity. More closely spaced sampling for Foraminifera, such as done by Haig (2003) for the Quinlan Shale, is required before the cyclic pattern can be fully understood and to determine the positions of maximum flooding intervals in each of the cycles. Based on the foraminiferal palaeobathymetric model established by Haig (2003) for the Quinlan Shale, the deepest water intervals probably incorporate the levels of S1–S3, S5, S6–S7, S9 and S10. These contain an association of *Sansabaina elegantissima* and *Lagenammina hemisphaerica* found only in the “Lower Offshore Zone” of the Quinlan–Shale model.

Age determination

Because of the very conservative nature of the morphologies of the foraminiferal genera (Haig & McCartain 2010) and their long time ranges, the siliceous agglutinated types from the Baker Formation cannot be used for correlation to the international chronostratigraphic scheme (GTS v. 2016.12; www.stratigraphy.org). The age of the Baker Formation relies on the presence of ammonoids within depositional cycle 5 at localities away from the type section.

Much discussion has centred on the stratigraphic positions of the ammonoids *Daubichites goochi* (Teichert), *Agathiceras applanatum* Teichert, *Popanoceras* sp., and

Paragastrioceras wandageense Teichert (see Teichert 1941, 1944, Glenister & Furnish 1961, Cockbain 1980, Archbold & Dickins 1989, Archbold 1998). Although Teichert (1941, 1944) was confident that all the genera were from his “*Linoproductus* stage” their precise localities are now uncertain, and it is possible that some of the rare specimens came from scree that may have moved from their original stratigraphic position. His local stage nomenclature preceded the code of lithostratigraphic nomenclature formulated in the 1950s that was followed in later geological mapping in the region (e.g. Condon 1954, 1967). A diverse fossil assemblage characterizes the “*Linoproductus* stage” including Bryozoa, crinoids (*Calceolospingia*), various brachiopods including the *Linoproductus* of Teichert (placed within *Canacrinella* by Archbold 1983), and bivalves. The stage was underlain by a stratigraphic interval with relatively sparse assemblages dominated by bivalves (the *Schizodus* stage of Teichert 1941). It is clear that the fauna of the “*Linoproductus* stage” comes from fossiliferous beds found at widespread localities in the lower part of the Coolkilya Sandstone (see compilation of Skwarko 1993, and stratigraphic logs of Condon 1967). As discussed by Leonovo (2011) *Daubichites* is indicative of the Roadian Stage of the Guadalupian Series (Middle Permian, 268.8±0.5 – 272.95±0.11 Ma, GTS v 2016/12). In the absence of any other age information, depositional cycle 5, including the Baker Formation, is placed within the Roadian.

Organic geochemistry

Four of the 10 samples (S1, S5–7) were analysed and yielded moderate total organic carbon values (TOCs) of 1.04 – 2.23%. RockEval data shows: (1) the pyrogram peak “S₂” at a low 0.10 – 0.22 mg/gm rock, a parameter recording the volume of hydrocarbons that formed during thermal pyrolysis of the sample and a measure of the amount of hydrocarbons that still may be produced if thermal maturation continues; (2) the hydrogen index “HI” at a very low 5–10, calculated from 100 × S₂/TOC,

indicating the potential to generate oil and reflecting the type of organic material (kerogen) in the rock; and (3) the oxygen index OI at 60–66, calculated from $100 \times S_3/TOC$ where peak “S₃” on the pyrogram measures the amount of CO₂ emitted during thermal breakdown of the kerogen (McCarthy *et al.* 2011). These values suggest that the organic content either has been greatly affected by weathering or that the original depositional environment was dominated by decomposed plant material—either reason could explain the lack of calcareous foraminifera in this section. Our results suggest the poor values from about this level in Kennedy Range 1, the only well from which analyses of the upper Byro Group are available, are not necessarily a good indication of the hydrocarbon generating potential of the upper part of the group. Further drilling is required to provide unweathered samples to properly evaluate the potential of this interval.

One sample (S5) analysed for vitrinite reflectance yielded a mean value of 0.55% indicating the section lies above the early oil-generating window with burial unlikely to have exceeded 1 km, of which at least half can be accounted for by the overlying 550–750 m thick Middle Permian Kennedy Group (Hocking *et al.* 1987). This amount of burial is relatively low thereby suggesting relatively low compression of mudstone in the Baker Formation consistent with the well-preserved, at least partially inflated, foraminiferal tests.

DEPOSITIONAL ENVIRONMENT

Haig (2004) and Haig *et al.* (2017) interpreted the depositional setting of the Byro Group as a narrow, shallow, interior sea with a very low-gradient seafloor and lacking a shelf to basin topography. The absence of a shelly marine fauna in much of the sand facies, except in relatively few isolated beds, and the abundance and diversity of siliceous agglutinated Foraminifera in carbonaceous muds deposited below wave base suggest an interior sea with estuarine-like environments such as in the present-day Baltic Sea (Kunzendorf & Larsen 2002; Haig 2003, 2004). At times salinity may have fluctuated depending on variable inflow of freshwater. Because of the narrow wave-fetch environment, fair-weather and storm-wave bases (i.e., the mud–sand interface on the seafloor) may have been very shallow (e.g. a few metres).

Within the carbonaceous mud facies of the Baker Formation, the persistent high abundance and relative high diversity (compared to the fauna known elsewhere in the Byro Group) of siliceous agglutinated Foraminifera and the very sparse thin-shelled macrofauna (bivalves) suggest that hyposaline conditions prevailed during deposition. The large robust foraminiferal tests (Figs. 5, 6) indicate that the seafloor was above the anaerobic zone. Changes in faunal composition through the mudstone section may have been caused by a complex interplay of environmental factors including fluctuations in water depth, turbidity, acidification of bottom water because of variable carbonaceous content, as well as dissolved oxygen and salinity. A better understanding of these factors will only be gained through more detailed study of the Baker Formation at this and other localities as well as similar studies of other formations in the Byro Group.

RECORD OF FORAMINIFERA

Family Psammosphaeridae Haeckel 1894

Genus *Psammosphaera* Schulze 1875

Type species: Psammosphaera fusca Schulze 1875.

Psammosphaera hockingi n. sp.; Figs. 5a–d.

2004 *Psammosphaera* sp. 1, Dixon & Haig, p. 320, pl. 2, figs. 7, 8.

Type material: Holotype, UWA172001, Fig. 5b, from S10A about 2 m below top of Baker Formation at type section (Fig. 4).

Derivation of name: Named in honour of Roger Hocking for his contributions to understanding the stratigraphy and sedimentology of the Byro Group, including the Baker Formation.

Diagnosis: A Permian species of *Psammosphaera* with test diameter to at least 0.83 mm; coarsely agglutinated wall with very rough surface composed of a mosaic of few angular to subangular quartz grains up to at least 540 µm diameter that are among the coarsest of any grains incorporated in the agglutinated tests of the accompanying foraminiferal assemblage; one or two variable openings in some tests.

Description: Test usually inflated with little deformation compared to the tests of accompanying species; globular, up to at least 0.83 mm in diameter, with very rough surface. Wall composed of a mosaic of angular to subangular quartz grains with a few larger grains up to at least 0.83 mm in diameter forming most of the surface and with finer grains packed in the interstices between the large grains. Some tests have one or two openings that are slit-shaped, oval, or approximately circular in outline. No apertural neck or distinct lip is developed.

Comparisons: The coarse-grained *Proteonina arenosa* Crespin (1958, p. 38, pl.2, figs. 6, 7), from the Byro Group in the Merlinleigh and Byro Sub-basins, differs in having an “apertural protuberance”. *Psammosphaera pusilla* Parr (1942, p. 106, pl.1, figs. 6, 7) differs with a much finer grained agglutinated wall.

Previous illustrated Western Australian records: Dixon & Haig (2004 as *Psammosphaera* sp.; Carrandibby Formation, Byro Sub-basin).

Genus *Thuramminoides* Plummer 1945

Type species: Thuramminoides sphaeroidalis Plummer 1945.

Thuramminoides sphaeroidalis Plummer 1945; Figs. 5e, f.

1945 *Thuramminoides sphaeroidalis* Plummer, p. 218, 219, pl.15, figs. 4 (holotype), 5–10.

Remarks. The holotype of *Psammosphaera pusilla* Parr (1942, p. 106, pl. 1, fig. 6; reillustrated with SEM image by Palmieri in Skwarko 1993, pl. 1, fig. 5) has a very fine-grained wall similar to *Thuramminoides sphaeroidalis* and probably belongs within this species.

Previous illustrated Western Australian records: Crespin (1958; Byro Group, Merlinleigh Sub-basin; Noonkanbah Formation, Canning Basin); Belford (1968; undifferentiated Byro Group, Merlinleigh Sub-basin);

Palmieri in Skwarko 1993; re-illustration of figured specimens of Crespin 1958); Haig (2003; type section of Quinannie Shale, Merlinleigh Sub-basin); Dixon & Haig (2004; Callytharra Formation, Byro Sub-basin).

Family Saccamminidae Brady 1884

Genus *Lagenammina* Rhumbler 1911

Type species *Lagenammina laguncula* Rhumbler 1911.

Lagenammina sp.; Figs. 5g–k.

Remarks: The specimens appear similar to the Western Australian Permian tests identified by Crespin (1958, pl. 2, figs. 8, 10) as *Pelosina hemisphaerica* Chapman & Howchin. This species was based on a deflated specimen (Chapman & Howchin 1905, p. 6, pl. 12, figs. 2a, b) with short neck from the Permian of the Hunter Valley in New South Wales. Because the degree of variability, particularly in the length and degree of taper of the neck and in wall structure, among topotypes of *P. hemisphaerica* is poorly understood the present species is left under open nomenclature.

Previous illustrated Western Australian records: Crespin (1958; Byro Group, Merlinleigh Sub-basin; Noonkanbah Formation, Canning Basin; as *Pelosina hemisphaerica*). Haig (2003 as *Lagenammina* sp.; Quinannie Shale, Merlinleigh Sub-basin).

Genus *Placentamina* Thalmann 1947

Type species: *Reophax placenta* Grzybowski 1898.

Placentamina ampulla (Crespin 1958); Figs. 5l–m.

1958 *Pelosina ampulla* Crespin, p. 42, 43, pl. 2, figs. 1 (holotype), 2, 3.

Previous illustrated Western Australian records: Crespin (1958, as *Pelosina*; Coyrie Formation and Bulgadoo Shale, Byro Group, Merlinleigh Sub-basin); Haig (2003, as *Placentamina* sp.; Quinannie Shale, Byro Group, Merlinleigh Sub-basin). Dixon & Haig (2004 as *Placentamina* sp.; Callytharra Formation, Byro Sub-basin).

Family Bathysiphonidae Avnimelech 1952

Genus *Psammosiphonella* Avnimelech 1952

Type species: *Bathysiphon arenaceus* Cushman 1927a.

Psammosiphonella sp.; Figs. 5n–p.

Remarks: This species bears some resemblance to *Hyperammina* (?) *rudis* Parr (p.105, pl. 1, fig. 3, holotype; re-illustrated as a SEM image by Palmieri in Skwarko 1993, pl. 1, fig. 12). However re-examination of the holotype of Parr's species shows that it has a closed initial end with distinct proloculus. The specimens recorded here have coarsely agglutinated tubular tests open at both ends.

Previous illustrated Western Australian records: Crespin (1958 as *Hyperamminita rudis*; Callytharra Formation and Madeline Formation of Byro Group, Byro Sub-basin; Bulgadoo Shale and Wandagee Formation of Byro Group, Merlinleigh Sub-basin; Noonkanbah Formation, Canning Basin).

Family Hyperamminoididae Loeblich & Tappan 1984

Genus *Giraliarella* Crespin 1958

Type species: *Giraliarella angulata* Crespin 1958.

Giraliarella rhomboidalis Crespin 1958; Figs. 5q, r.

1958 *Giraliarella rhomboidalis* Crespin, p. 58, pl. 9, figs. 9 (holotype), 10.

Previous illustrated Western Australia records: Crespin (1958; upper Wandagee Formation, Byro Group, Merlinleigh Sub-basin; Noonkanbah Formation, Canning Basin).

Genus *Hyperamminoides* Cushman & Waters 1928b

Type species: *Hyperamminella elegans* Cushman & Waters 1928a.

Hyperamminoides elegans (Cushman & Waters 1928a); Figs. 5s, t.

1928 *Hyperamminella elegans* Cushman & Waters 1928a, p. 36, pl. 4, figs. 3, 4 (holotype).

Previous illustrated Western Australia records: Crespin (1958 as *Hyperammina*; Callytharra Formation, Merlinleigh Sub-basin; Coyrie Formation, Bulgadoo Shale, Wandagee Formation of Byro Group, Merlinleigh Sub-basin; Noonkanbah Formation, Canning Basin); Belford (1968 as *Hyperammina*; Lyons Group, Carrandibby Formation, Keogh Formation, Madeline Formation in subsurface Byro Sub-basin; undifferentiated Byro Group in subsurface Merlinleigh Sub-basin); Dixon & Haig (2004 as *Hyperamminoides?* sp.; Callytharra Formation, Byro Sub-basin).

Genus *Kechenotiske* Loeblich & Tappan 1984

Type species: *Hyperamminoides expansus* Plummer 1945.

Kechenotiske expansa (Plummer 1945); Figs. 5v, w.

1945 *Hyperamminoides expansus* Plummer, p. 223, 224, pl. 16, figs. 1 (holotype), 2–6.

Previous illustrated Western Australian records: Crespin (1958 as *Hyperammina*; Bulgadoo Shale, Baker Formation of Byro Group, Merlinleigh Sub-basin; ?Grant Group, Nura Nura Member of Poole Sandstone, Noonkanbah Formation, Canning Basin); Belford (1968 as *Hyperammina*; Carrandibby Formation, Callytharra Formation in subsurface Byro Sub-basin).

Kechenotiske hadzeli (Crespin 1958); Fig. 5u.

1958 *Hyperammina hadzeli* Crespin, p. 51, 52, pl. 5, figs. 6 (holotype), 7–10.

Previous illustrated Western Australian records: Crespin (1958 as *Hyperammina*; Callytharra Formation, Byro Sub-basin); Belford (1968 as *Hyperammina*; Callytharra Formation in subsurface Byro Sub-basin); Haig (2003; Quinannie Shale of Byro Group, Merlinleigh Sub-basin). Dixon and Haig (2004; Callytharra Formation, Byro Sub-basin).

Genus *Sansabaina* Loeblich & Tappan 1984

Type species: *Hyperammina elegantissima* Plummer 1945.

Sansabaina elegantissima (Plummer 1945); Figs. 5x, y.

1945 *Hyperammina elegantissima* Plummer, p. 222, 223, pl. 15, figs. 17 (holotype), 18–25.

Previous illustrated Western Australia records: Crespin (1958 as *Hyperammina*; Nangetty Formation, Irwin Sub-basin; Callytharra Formation, Byro Sub-basin; Callytharra Formation, Merlinleigh Sub-basin. Haig (2003; Quinannie Shale of Byro Group, Merlinleigh Sub-basin).

Sansabaina? acicula (Parr 1942); Fig. 5z.

1942 *Hyperamminoides acicula* Parr, p. 105, 106, pl. 1, figs. 4, 5, pl. 2, fig. 4 (holotype).

Previous illustrated Western Australian records: Parr (1942 as *Hyperamminoides*; “*Lingula* beds, now included in Quinannie Shale, Byro Group, Merlinleigh Sub-basin); Crespin (1958 as *Hyperammina*; Coyrie Formation, Mallens Sandstone, Bulgadoo Shale, Cundlego Formation, Wandagee Formation, Baker Formation of Byro Group and Coolkilya Sandstone of Kennedy Group, Merlinleigh Sub-basin); Haig (2003 as *Sansabaina?*; Quinannie Shale of Byro Group, Merlinleigh Sub-basin).

Family Ammodiscidae Reuss 1862

Genus *Ammodiscus* Reuss 1862

Type species: *Ammodiscus infimus* L.G. Bornemann 1874 (= *Involutina silicea* Terquem 1862).

Ammodiscus erugatus Crespin, 1958; Figs. 6a, b.

1958 *Ammodiscus erugatus* Crespin, p. 66, 67, pl. 12, figs. 1 (holotype), 2, 3.

Previous illustrated Western Australian records: Crespin (1958; Noonkanbah Formation Liveringa Group, Canning Basin).

Ammodiscus nitidus Parr 1942; Figs. 6c–f.

1942 *Ammodiscus nitidus* Parr, p. 103, pl. 1, figs. 1a, b (holotype; re-illustrated as a SEM image by Palmieri in Skwarko 1993, pl. 2, fig. 26).

Remarks: Crespin (1958, p. 68, 69) noted that the initial (central) portion of the test on one side is often attached to a mica flake (e.g. Figs. 6e, f). Other specimens in the Baker Formation have initial portions attached to a large quartz grain (e.g. Fig. 6d).

Previous illustrated Western Australian records: Parr (1942; *Lingula* beds, now included within the Quinannie Shale, Byro Group; Merlinleigh Sub-basin); Crespin (1958; Callytharra Formation, Warrawaringa Formation, Madeline Formation, Byro Sub-basin; Callytharra Formation, Coyrie Formation, Mallens Sandstone, Bulgadoo Shale, Cundlego Formation, Wandagee Formation, Baker Formation, Merlinleigh Sub-basin; Nura Nura Member of Poole Sandstone, Noonkanbah Formation, Dora Shale, Canning Basin); Belford (1968; Callytharra Formation, Keogh Formation in subsurface Byro Sub-basin; undifferentiated Byro Group in subsurface Merlinleigh Sub-basin); Palmieri in Foster *et al.* (1985; Fossil Cliff Member of Holmwood Shale, Irwin Sub-basin); Haig (2003; Quinannie Shale of Byro Group, Merlinleigh Sub-basin); Dixon & Haig (2004; Callytharra Formation, Byro Sub-basin).

Ammodiscus wandageeensis Parr, 1942; Figs. 6g, h.

1942 *Ammodiscus wandageeensis* Parr, p. 102, pl. 2, fig. 1 (holotype; re-illustrated as a SEM image by Palmieri in Skwarko 1993, pl. 2, fig. 27).

Previous illustrated Western Australia records: Parr (1942; *Lingula* beds, now included within the Quinannie Shale, Byro Group; Merlinleigh Sub-basin); Crespin (1958, Quinannie Shale, Wandagee Formation, ?Baker Formation of Byro Group, Merlinleigh Sub-basin); Belford (1968; lower Nunnery Sandstone in subsurface Byro Sub-basin); Haig (2003; Quinannie Shale of Byro Group, Merlinleigh Sub-basin).

Family Hormosinidae Haeckel 1894

Genus *Hormosinoides* Saidova 1975

Type species: *Hormosinoides perpastus* Saidova 1975.

Hormosinoides belfordi (Crespin 1958); Figs. 6j, k.

1958 *Reophax belfordi* Crespin, p. 60, 61, pl. 10, figs. 8–11.

Remarks: The species is transferred to *Hormosinoides* because of the straight test axis, cylindrical chambers that show a uniform, progressive increase in size and the absence of a distinct apertural neck. As based on the neotype of its type species (see Brönnimann & Whittaker 1980, p. 262–264, figs. 2, 5), *Reophax* has a more irregular test axis (slightly arcuate), more irregularly shaped chambers (irregularly pyriform) with abrupt increases in chamber size, and the final chamber drawn out into a distinct apertural neck. Rauzer-Chernousova & Reitlinger (1986) included the species in their new genus *Kunklerina* that is considered a junior synonym of *Hormosinoides*.

Previous illustrated Western Australian records: Crespin (1958, undifferentiated Byro Group, Merlinleigh Sub-basin); ?Dixon & Haig (2004 as *Reophax?* sp.; Carrandibby Formation, Byro Sub-basin).

Hormosinoides sp. cf. *H. expatiatius* (Plummer 1945);

Figs. 6p, q.

cf. 1945 *Reophax expatiatius* Plummer 1945, p. 228, pl. 17, figs. 4 (holotype), 5, 6.

Remarks: This species has a much larger test that recorded by Plummer (1945) for *H. expatiatius* from the Pennsylvanian of Texas. It resembles the American species in test and chamber shape and in its coarsely agglutinated wall.

Genus *Reophax* de Montfort 1808

Type species: *Reophax scorpiurus* de Montfort 1808 (see revision and selection of neotype by Brönnimann & Whittaker 1980, p. 262–264, figs. 2, 5).

Reophax tricameratus Parr 1942; Figs. 6l–o.

1942 *Reophax tricameratus* Parr, p. 109, pl. 1, fig. 13 (holotype; re-illustrated as a SEM image by Palmieri in Skwarko 1993, pl. 3, fig. 8).

Previous illustrated Western Australia records: Parr (1942, “*Lingula* beds, now included in Quinannie Shale, Byro Group, Merlinleigh Sub-basin); Crespin (1958, Lyons Group, Callytharra Formation, Coyrie Formation,

Quinnanie Shale of Byro Group, Merlinleigh Sub-basin; Madeline Formation, Byro Sub-basin; Noonkanbah Formation, Liveringa Group, Canning Basin). Haig (2003; Quinnanie Shale of Byro Group, Merlinleigh Sub-basin).

Family Haplophragmoididae Maync 1952

Remarks: The definition of this family follows Haig & McCartain (2010, p. 375).

Genus *Ammobaculites* Cushman 1910

Type species: *Spirolina agglutinans* d'Orbigny 1846.

Ammobaculites wandageensis Crespin 1958; Figs. 6r, s.

1941 *Ammobaculites wandageensis* Crespin, p. 74, 75, pl. 14, figs. 1 (holotype), 2, 3.

Previous illustrated Western Australian records: Crespin (1958; Coyrie Formation, Bulgadoo Shale of Byro Group, Merlinleigh Sub-basin; Noonkanbah Formation, Canning Basin); Haig (2003 as *Ammobaculites woolnoughi*; Quinnanie Shale of Byro Group, Merlinleigh Sub-basin).

Family Spiroplectamminidae Cushman 1927b

Genus *Spiroplectammina* Cushman 1927b

Type species: *Textularia agglutinans* d'Orbigny var. *biformis* Parker & Jones 1865.

Spiroplectammina carnarvonensis Crespin 1958; Fig. 6t.

1958 *Spiroplectammina carnarvonensis* Crespin, p. 76, 77, pl. 22, figs. 7 (holotype), 8, 9.

Previous illustrated Western Australian records: Crespin (1958; Coyrie Formation, Bulgadoo Shale, Cundlego Formation of Byro Group, Merlinleigh Sub-basin); Haig (2003 as *Spiroplectammina eccentrica*; Quinnanie Shale of Byro Group, Merlinleigh Sub-basin); Dixon & Haig (2004 as *Spiroplectammina eccentrica*; Callytharra Formation, Byro Sub-basin).

Family Verneuilinoididae Suleymanov 1973

Remarks. This family includes organic-cemented siliceous agglutinated species characterised by the genus *Verneuilinoides* Loeblich & Tappan. Early Permian genera that are best placed within the family include *Aaptotoichus* Loeblich & Tappan, *Digitina* Crespin & Parr, *Gaudryinopsis* Podobina and *Palustrella* Brönnimann, Whittaker & Zaninetti. These are the earliest representatives of the Verneuilinoididae.

Genus *Palustrella* Brönnimann, Whittaker & Zaninetti 1992

Type species: *Textularia palustris* Warren 1957.

Palustrella improcera (Crespin 1958); Figs. 6u–x.

1958 *Textularia improcera* Crespin, p. 78, 79, pl. 15, figs. 8 (holotype), 9.

Previous illustrated Western Australian records: Crespin (1958; Coyrie Formation, Baker Formation of Byro Group, Merlinleigh Sub-basin).

Family Trochamminidae Schwager 1877

Genus *Trochamminopsis* Brönnimann 1976

Type species: *Trochammina pusilla* Höglund 1947.

Trochamminopsis subobtusa (Parr 1942); Figs. 6y–zc.

1942 *Trochammina subobtusa* Parr, p. 109, pl. 1, figs. 14a–c (holotype; re-illustrated by a SEM image by Palmieri in Skwarko 1993, pl. 4, fig. 9).

Previous illustrated Western Australian records: Parr (1942 as *Trochammina*; "Lingula beds, now included in Quinnanie Shale, Byro Group, Merlinleigh Sub-basin); Crespin (1958 as *Trochammina*; Madeline Formation, Byro Sub-basin; Bulgadoo Shale, Cundlego Formation, Quinnanie Shale, Wandagee Formation of Byro Group, Merlinleigh Sub-basin; Noonkanbah Formation, Canning Basin); Belford (1968 as *Trochammina*; undifferentiated Byro Group in subsurface Merlinleigh Sub-basin); Haig (2003; Quinnanie Shale of Byro Group, Merlinleigh Sub-basin).

CONCLUSIONS

1. All Foraminifera recovered from the type section of the Baker Formation belong to organic-cemented siliceous agglutinated families and include 21 species attributed to *Psammosphaera*, *Thuramminoides*, *Lagenammina*, *Placentammina*, *Psammosiphonella*, *Giraliarella*, *Hyperamminoides*, *Kechenotiske*, *Sansabaina*, *Ammodiscus*, *Hormosinoides*, *Reophax*, *Ammobaculites*, *Spiroplectammina*, *Palustrella* and *Trochamminopsis*.

2. One new species, *Psammosphaera hockingi* n. sp. is described. Another species, *Hormosinoides* sp. cf. *H. expatiatius* (Plummer 1945), is new but represented by too few specimens to be formally described. All other species have been recorded from formations stratigraphically below the Baker Formation in Western Australia.

3. Faunal composition changes frequently through the mudstone succession in the Baker Formation. This suggests variable marine conditions in the depositional environment, for example in water depth, salinity and dissolved oxygen. The foraminiferal assemblage is consistent with brackish estuarine-like conditions in the interior sea.

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